INSPIRATION FOR FUTURE AUTONOMOUS SPACE SYSTEMS

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1. THE FUTURE NASA MISSION CHALLENGE

NASA is embarking on a new phase of space exploration. In the solar system, an initial reconnaissance of all of the planets except Pluto has been accomplished. In the next phase of planetary exploration, the emphasis will be on direct, i.e., in-situ scientific investigation in the remote environments. In the next phase of astrophysics investigation, the emphasis is on new observing instruments, often based on principles of interferometry, to accomplish unprecedented resolution in remote observing. A theme that runs through all of these science missions is the search for life.

The development of autonomy capabilities is on the critical path to addressing a set of vastly important strategic technical challenges arising from the future NASA mission set: reduction of mission costs, increased efficiency in the return of quality science products, and the launching of a new era of solar system exploration characterized by sustained presence, in-situ science investigations and missions accomplished via multiple, coordinated space platforms. These new classes of space exploration missions, as a rule, require new capabilities and technologies.

1.1 Future Missions and Autonomy

Mars is a primary target for future exploration, and certainly has captured the interest of the general public. The set of Mars missions under development differ from previous space exploration in one important aspect: they are being conceived as a collective whole, with the establishment and evolution of infrastructure at Mars as an important sub-goal. Such proposed infrastructure includes permanent science stations on the surface, propellant production plants, and a network of communications satellites in orbit to extend internet-like capability to Mars, and to enable the coordination of an array of heterogeneous, autonomous agents as explorers: rovers, balloons, airplanes, perhaps even subsurface devices. No longer would each mission be conceived and executed in isolation, but through a combination of in situ and constellation mission concepts humanity's presence at Mars would continually expand, culminating in the arrival and safe return of the first human explorers.

Europa is a notable focus for future exploration, second only to Mars as a target of interest within the solar system. The reason, of course, is the possibility that a liquid water ocean may exist beneath its surface, with obvious implications for the search for life. Three mission concepts for Europa exploration are at various stages of maturity: the Europa Orbiter mission, approved and set to launch in 2003, which should resolve the question of whether the subsurface ocean exists or not, followed by the Europa Lander, and perhaps by a Europa Cyrobot/Hydrobot mission. The Lander would have similar challenges of safe landing and surface operations as described above, plus the additional complication of survivability in the intense radiation environment at Europa, deeply embedded in the Jovian magnetosphere. If the Europan ocean does indeed exist, the Cryobot/Hydrobot mission concept involves melting through the ice surface of Europa, then releasing an underwater submersible to reach and explore the ocean floor, looking for signs of life. The submersible would require high degrees of autonomy, including onboard algorithms embodying knowledge of biosignatures, in order to perform its mission.

2. THE EMERGENCE OF AUTONOMY

Intelligent, highly autonomous space platforms will evolve and deploy in major phases. The first phase involves automation of the basic engineering and mission accomplishment functions of the space platform. The relevant capabilities include mission planning and resource management, health management and fault protection, and guidance, navigation and control. Stated differently, these autonomous capabilities will make the space platform *self-commanding* and *self-preserving*. At this point, mission accomplishment is becoming largely autonomous, and cost savings is seen in the form of reduced, shared ground staffing which responds on demand to the spacecraft's beacon-based requests for interaction. Also in this phase, the first elements of *science-directed autonomy* will appear.

Work on automating the spacecraft will continue into challenging areas like greater onboard adaptability in responding to events, and operation of the multiple free-flying elements of space-based telescopes and interferometers. In addition, in the next phase of autonomy development and deployment, a portion of the scientist's awareness, i.e., an observing and discovery presence, will begin to move onboard. At this point, the space platform begins to become *self-directing,* and can respond to uncertainty within the mission context, a prerequisite for moving beyond reconnaissance to interactive, in situ exploration. Ultimately, a significant portion of the information routinely returned from platforms would not simply and strictly match features of stated prior interest, but would be deemed by the onboard software to be "interesting" and worthy of further examination by appropriate science experts on the ground.

For a survey of recent autonomy technology activities at NASA, see [1].

Beyond these initial phases, we can project a phase where space platforms become web nodes, with direction interaction enabled among space platforms, the science community, and the general public. Interested users may "register" with autonomous spacecraft to learn about just-breaking results.

The next phase may involve self-organizing constellations of space platforms consisting of heterogeneous assets performing joint, coordinated execution of mission objectives, with self-calibration and adaptation enabled at the level of the mission.

2.1 The Remote Agent

The most notable and successful effort in spacecraft autonomy development at NASA to date has been the Remote Agent, a joint technology development project by NASA Ames Research Center and the Jet Propulsion Laboratory (JPL) [2]. The Remote Agent Experiment was conducted on the New Millennium Deep Space One (DS1) spacecraft in May 1999 [3], a mission whose primary goal was to flight validate new technologies.

The demonstration objectives of the Remote Agent Experiment (RAX) on DS1 included nominal operations with goal-oriented commanding, closed-loop plan execution, onboard failure diagnosis and recovery, onboard planning following unrecoverable failures, and system-level fault protection. All of the technology validation objectives for RAX were accomplished. Additional details may be found in [4]. The Remote Agent was a co-winner of the NASA Software of the Year Award in 1999.

2.2 Some Definitions

Automation applies to the creation of functionality (typically via algorithms) which can be fully defined independent of the context in which the functionality will be deployed, or when the context (e.g., the remote environment) can be modeled with sufficient confidence that the required functionality is well understood.

Autonomy, on the other hand, applies to the creation of functionality (typically via reasoning or inference capability) which is designed to be effective when context is important, and when the ability to model context (again, e.g., the remote environment) is limited. Knowledge and importance of context is the key consideration for distinguishing the need for automation vs. autonomy.

We can conceive of a form of autonomy that takes the next step: allowing for *evolving* functionality after deployment. This evolution would take place within the resources of the remote autonomous system itself (i.e., not via uplinked software patches or new loads) and would be driven by feedback from and understanding of the remote environment. A possible term for this next-generation form of autonomy is *flexibility*.

2.3 Flexible Systems

The concept of flexible systems is meant to enable *phase change* in the functionality of deployed space systems. Unlike current conceptions of autonomous systems, flexible systems would not have their functionality fixed at deployment time. Rather, the space of possible functionalities would continue to be explored after arrival in the remote environment, and would be responsive to both internal system changes and external environmental changes. Latent functionality would be explored first in software, and when well understood, would be "compiled" or implemented in hardware changes. Flexibility may ultimately imply a merging of hardware- and software-based capabilities, and directly supports goals for long-term survivability, continuing mission accomplishment and evolvability under changing circumstances and objectives. Within the model for flexibility, space systems may undergo several phase changes over their lifetime. Evolvability is an example of a characteristic exhibited by biological systems which may one day be embodied in our designed and engineered space systems to great advantage [5].

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